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Very Low Frequency Acoustic Detection of Submarines
[Unclassified Title]

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March 1977

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(S) This report examines the detectability of blade rate lines for several classes of Soviet submarines. The Naval Research Laboratory has measured low frequency (VLF) transmission loss and ambient noise at sites in the Atlantic Ocean and Norwegian Sea. The results are used to calculate the array gain necessary to detect present and future classes of Soviet submarines at these Atlantic Ocean and Norwegian Sea sites. The results are presented for submarine speeds of interest. The problem of array size needed to obtain necessary array gain and the problem of signal spatial coherence are considered.

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CONTENTS

VERY LOW FREQUENCY ACOUSTIC DETECTION OF SUBMARINES
[Unclassified Title]

Introduction

(S) As a submarine propels itself through the water, it radiates very low frequency acoustic power which is caused by the interaction of the propeller's blades, the water, and the hull. As the propeller rotates, the water pressure on the propeller blades varies due to irregularities in water flow between the propeller and hull. This pressure variation is enhanced at certain frequencies by resonance in the submarine hull. The resulting narrowband radiated power can be detected by spectral analysis of the acoustic signature. These spectal lines are known as "blade rate lines". Blade rate lines occur in the frequency region of about 5 to 20 Hz.

(S) At higher submarine speeds these lines can be very intense, often exceeding 170 dB//μPa @ 1m. At these low frequencies, the radiated power is not significantly attenuated by the ocean as it propagates. This suggests that blade rate lines might be useful for long range detections of transiting submarines.

(C) Submarines are normally detected by higher frequency acoustic radiation, which is caused by auxiliary equipment aboard the submarine. However, it is anticipated that better acoustic design will greatly reduce the amplitude of these auxiliary lines. This means that auxiliary lines will become harder to detect. Therefore, blade rate lines may become more important for detection purposes.

(S) It will later be seen that there are several areas of uncertainty which critically affect the conclusions of this report. The lack of certainty about foreign submarine source levels and limited ambient noise data in the 5 to 20 Hz region are problem areas. For example, no blade rate levels of Soviet submarines have been measured below 10 Hz., reference 1. Measurements above 10 Hz show considerable dispersion.

(C) This report uses environmental data recently gathered by NRL (references 2, 3, & 6). Both transmission loss and ambient noise data were obtained in the 5 to 20 Hz region at sites in the Atlantic Ocean and Norwegian Seas.

(U) Calculations with the sonar equation give the array gain ncessary to detect a particular class of Soviet submarine in the Atlantic Ocean and in the Norwegian Sea. The array gain needed for detection gives a good indication of VLF submarine detection feasibility.

(S) A general conclusion is that all Soviet submarines are readily detectable on their blade rate lines if they are moving fast

Note: Manuscript submitted February 18, 1977.

enough. Since there is an approximate one to one correspondence between submarine speed and blade rate frequency and since blade rate source levels increase rapidly with frequency, the required array gain has been computed at 1 Hz intervals for given ranges and for submarine speeds of interest.

Submarine Source Levels

(C) Source levels, bandwidths, turn-per-knot (TPK) ratios, and number of blades per propeller are given in reference 4 for many present and future classes of Soviet submarines. The Charley (SSGN), Victor (SSN), Yankee (SSBN), Delta-II (SSBN), future large SSN, and future SSGN classes are included in this report.

(C) Submarines do not radiate equally in all directions. The directionality of blade rate sound is given in reference 5 and is shown in figure 1. The dashed line in figure 1 represents the value of radiated sound averaged over aspect. This average is 5 dB below the peak value, which occurs at bow aspect.

(C) The submarine radiated sound levels given in reference 4 are for bow aspect. Therefore, the source levels given in reference 4 are reduced by 5 dB to convert bow aspect radiated sound to the expected value at a random aspect. The source levels of the several classes of submarines are given in Table 1. The numbers directly below the levels are the corresponding submarine speeds in knots. The C-V source levels are from the linear fit to measured data shown in figure 2, abstracted from reference 4. The other source levels are estimated using a semi-empirical model which takes hull resonance into account, reference 7. An example of this source level model is shown in figure 3, also from reference 4.

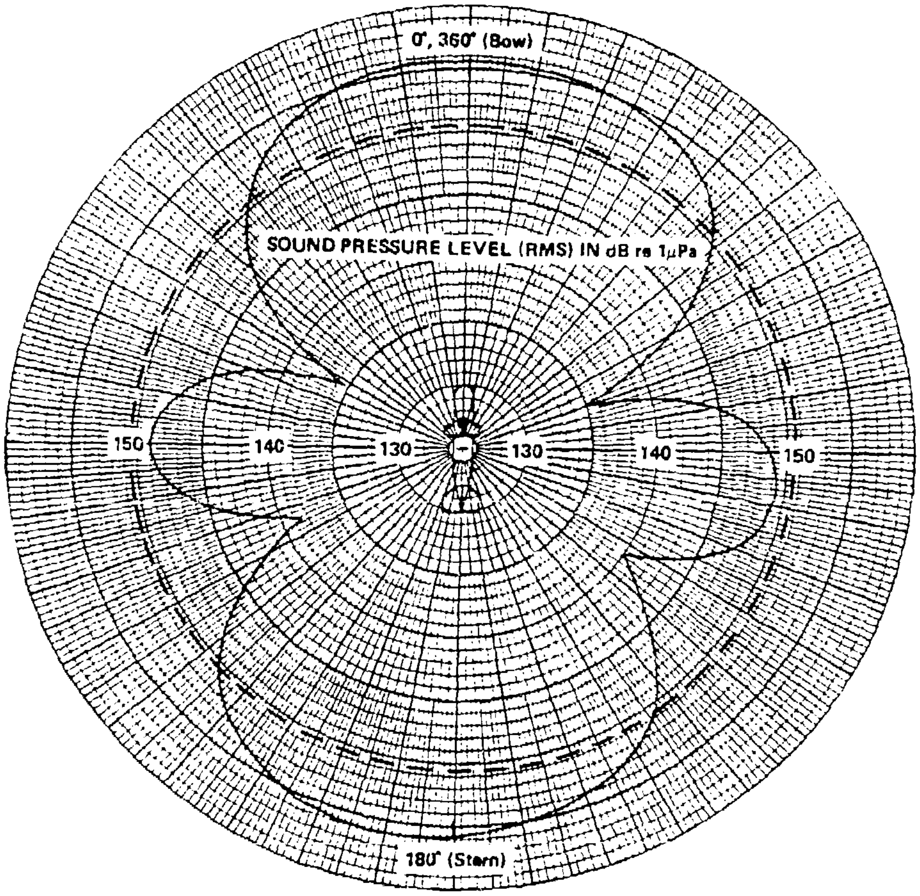
(C) The Standard Threat Assessment, reference 4, gives turn-per-knot ratios and number of propeller blades for the FUT SSN, FUT SSGN, and D-II classes of submarines. From these facts, one can compute the submarine speed from the blade rate frequency by:

SPEED(KTS) = 60* BLADE RATE (HZ)/(TPK RATIO*NUMBER OF BLADES). (1)

The TPK ratio varies with frequency, so that the use of equation 1 with a fixed TPK ratio is only an approximation.

(C) Table 2a below gives the conversion from blade rate to speed. For the C, V and Y classes the speeds are taken from Table 4.2, reference 4; for the other classes the speed was computed by equation (1) with a fixed TPK ratio from the Standard Threat Assessment, as shown in Table 2b.

(S) Line bandwidths and long term stability for blade rate lines are given in the Standard Threat Assessment. For the C, V and Y class submarines the blade rate line bandwidth is .004 to .07 Hz; the long



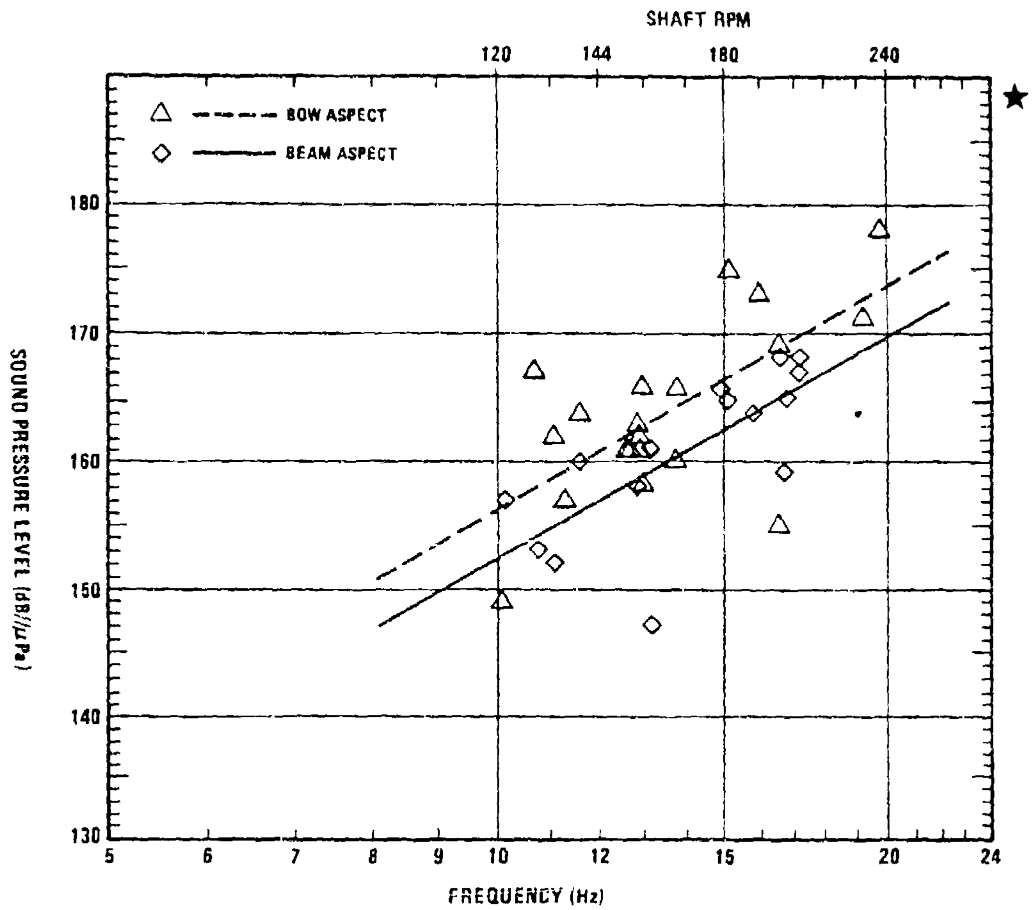
(C) Fig. 1 — Directivity pattern of radiated sound at ≈ 10 Hz (U)

Figure source: Low-Frequency Acoustic and Coupling Measurements of a Submarine Model (U), NSRDC Report C-4609.

TABLE 1: TABLE OF AVERAGE ASPECT RADIATED SOUND (dB//1μPa. @ 1m.) VS. FREQUENCY

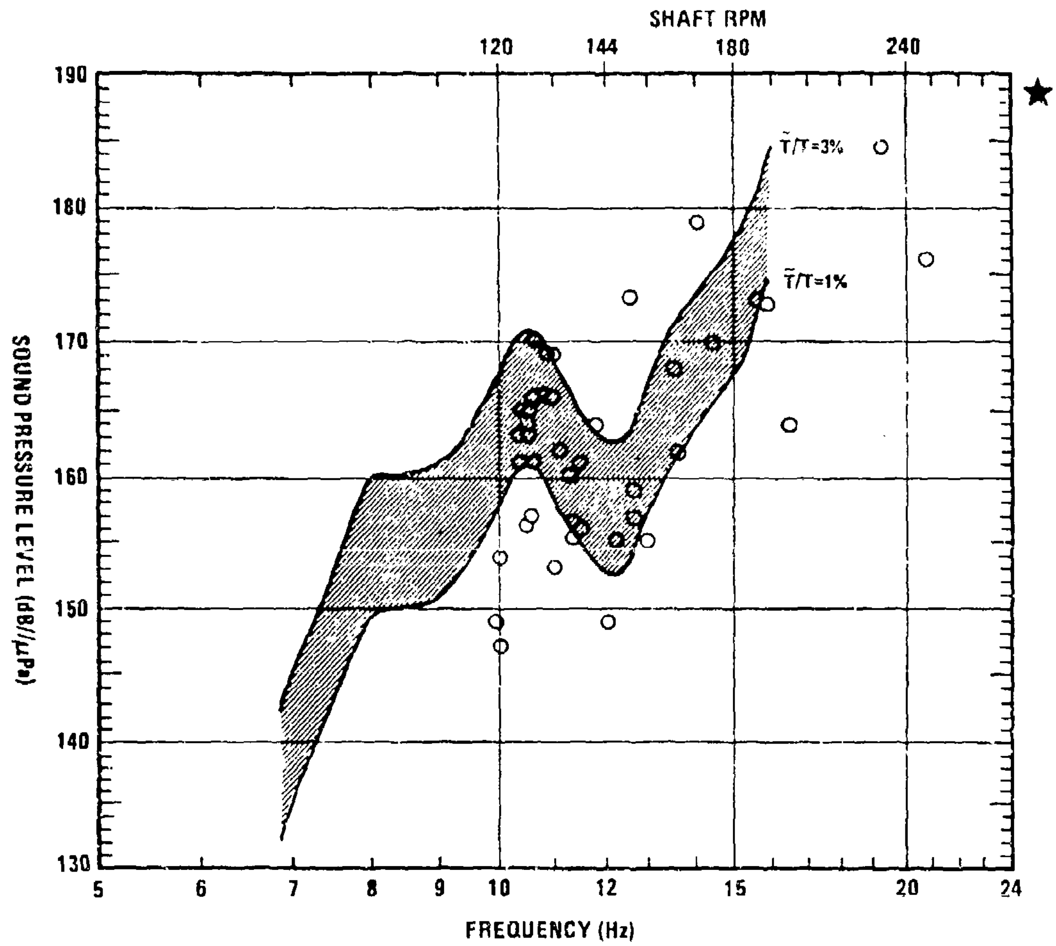
SUBMARINE CLASS	FREQUENCY (HZ.) 5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
FUT SSN	128.0	130.0	132.5	135.5	139.5	144.5	150.5	158.5	163.0	165.0	164.0	163.5	164.0	164.5	165.8	[illegible]	**
Speed (kts)	8.0	9.6	11.2	12.8	14.4	16.0	17.6	19.2	20.8	22.4	24.0	25.6	27.2	28.8	30.4	32.0	40.0
FUT SSGN	131.5	134.0	139.5	149.5	158.0	158.0	157.5	158.0	159.5	164.0	172.5	176.5	177.0	177.0	176.5	176.0	**
Speed (kts)	8.0	9.6	11.2	12.8	14.4	16.0	17.6	19.2	20.8	22.4	24.0	25.6	27.2	28.8	30.4	32.0	40.0
C-V	133.5	138.1	142.0	145.4	148.3	151.0	153.4	155.6	157.6	159.5	161.2	162.8	164.4	165.8	167.2	168.5	174.1
Speed (kts) C	5.1	6.3	7.4	8.6	9.7	10.9	12.1	13.3	14.6	15.8	17.0	18.3	19.5	20.8	22.0	23.3	**
Speed (kts) V	6.2	7.5	8.7	10.0	11.4	12.7	14.0	15.3	16.6	18.0	19.3	20.6	22.0	23.3	24.7	26.0	**
Y	125.0	129.0	133.0	149.5	150.5	158.0	158.0	152.0	136.5	163.0	167.0	173.0	175.0	176.5	178.0	180.0	185.0
Speed (kts)	5.7	6.9	8.1	9.3	10.6	11.9	13.1	14.4	15.7	17.0	18.3	19.6	21.0	22.3	23.6	25.0	**
D-II	131.0	143.0	148.5	145.7	147.7	152.0	161.0	167.0	167.0	166.5	166.0	166.0	166.5	167.0	168.0	169.0	177.0
Speed (kts)	6.0	7.2	8.4	9.6	10.8	12.0	13.2	14.4	15.6	16.8	18.0	19.2	20.4	21.6	22.8	24.0	30.0

** no data



(S) Fig. 2 — Blade rate frequency levels radiated from Charlie and Victor class submarines (S)

Figure source: ASW Standard Submarine Threat Assessment (U), CNO Serial Number 951G1/S166582, 1 January 1976.



(S) Fig. 3 — Blade rate frequency levels radiated from Soviet Yankee class submarines at bow aspect (S)

Figure source: ASW Standard Submarine Threat Assessment (U), CNO Serial Number 951G1/S166582, 1 January 1976.

TABLE 2.a: TABLE OF BLADE RATE FREQUENCY (HZ) VS. SPEED (KTS)

BLADE RATE FREQUENCY (HZ)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
SUBMARINE CLASS	SPEED (KTS)																
C	5.12	6.25	7.4	8.56	9.74	10.93	12.13	13.34	14.56	15.78	17.02	18.27	19.52	20.78	22.04	23.31	**
V	6.16	7.45	8.74	10.04	11.35	12.67	13.99	15.31	16.64	17.97	19.31	20.64	21.99	23.33	24.68	26.04	**
Y	5.65	6.86	8.10	9.34	10.6	11.87	13.14	14.43	15.72	17.02	18.33	19.64	20.96	22.29	23.62	24.95	**
D-II	6.0	7.2	8.4	9.6	10.8	12.0	13.2	14.4	15.6	16.8	18.0	19.2	20.4	21.6	22.8	24.0	30.
FUT SSGN	8.0	9.6	11.2	12.8	14.4	16.0	17.6	19.2	20.8	22.4	24.0	25.6	27.2	28.8	30.4	32.0	40.
FUT SSN	8.	9.6	11.2	12.8	14.4	16.0	17.6	19.2	20.8	22.4	24.0	25.6	27.2	28.8	30.4	32.0	40.

** no data

TABLE 2.b

	TPK	Number of Blades
C	~ 10.8	5
V	~ 9.4	5
Y	~ 9.9	5
D-II	10*	5
FUT SSGN	7.5*	5
FUT SSN	7.5*	5

speeds in Table 2a taken from Table 4.2, reference 4

* estimate; data meager

rec̲m s. . ility is .1 to .4 Hz. It is reasonable to assume similar li. b dwidth and stability for the future classes of submarines beirg co. . . .d. Thus a 0.1 Hz processing bandwidth, with 10 minute inte. ation ti e has been selected for the narrowband analyzer.

Enviro. al Data - Norwegian Sea

(S) In 1972 and 1973 the Propagation Branch of NRL's Acoustics Division carried out acoustic experiments in the Norwegian Sea (reference 3). These experiments produced transmission loss and ambient noise data. Transmission loss was measured by towing a projector and measuring the received acoustic signal on fixed bottom mounted hydrophones. Transmission loss was measured at 5, 10, 15, and 30 Hz. Ambient noise data was obtained at the same time by measuring the noise in frequency bands adjacent to the received signal. The transmission loss data from the different receivers was combined and regrouped according to frequency. Each group was fitted in a least squares sense to

$$TL(R) = 66.13 + 10\alpha \log_{10}(R) \tag{2}$$

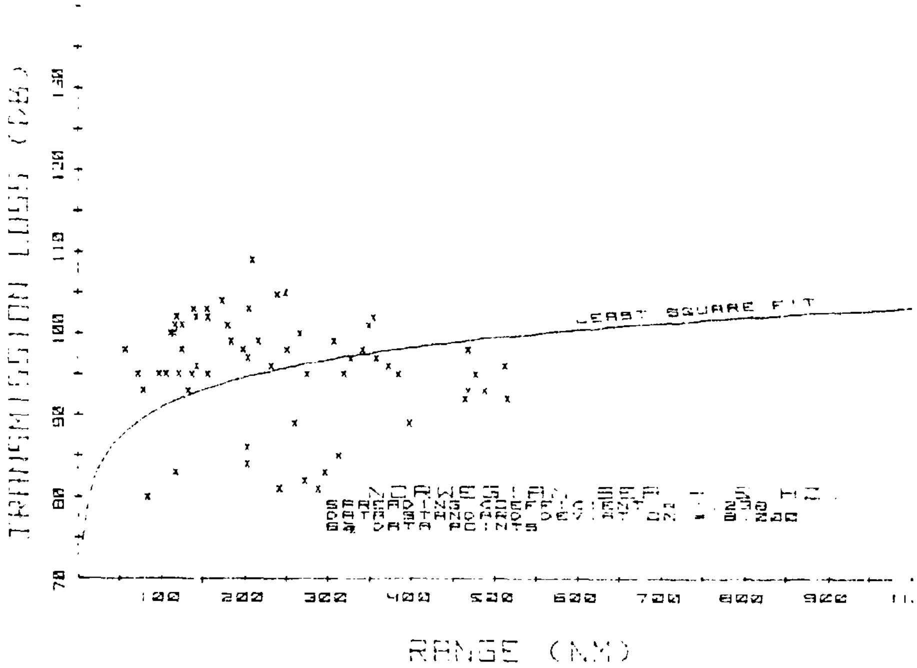
where α is the unknown spreading coefficient, R is the range in nautical miles and TL(R) is the mean transmission loss at range R. Figures 4a, 4b, 4c, and 4d give plots of the measured data and graph the least square fit. The standard deviation of each data set is included in figures 4. Equation (2) assumes spherical spreading to 1 nautical mile and spreading as the power α beyond 1 nautical mile. The values of α are given in Table 3 below for different frequencies.

TABLE 3

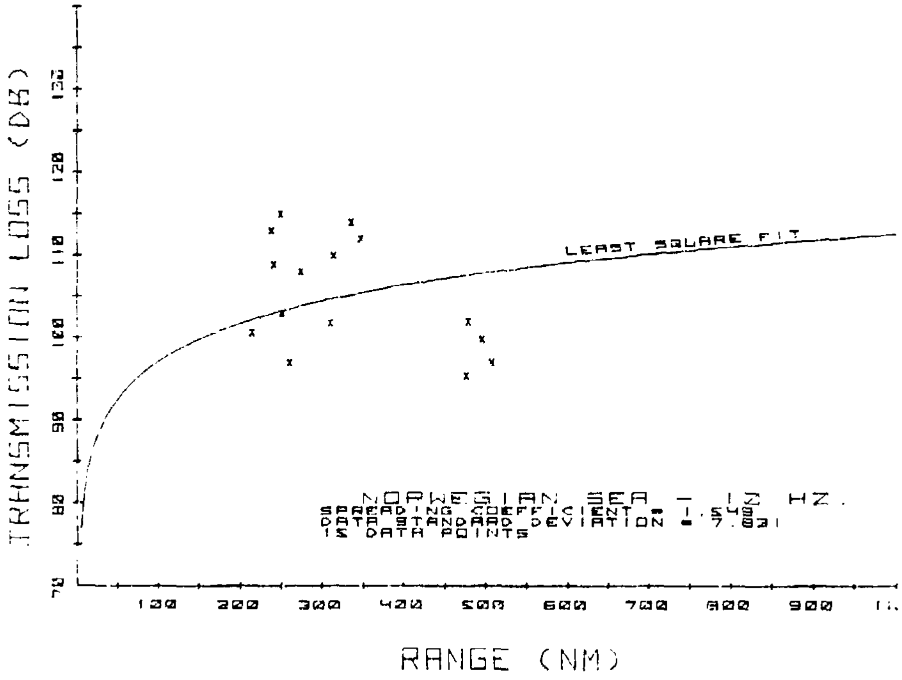
Values of Spreading Coefficient, α, in Norwegian Sea for Several Frequencies

Frequency (Hz)	α
5	1.24
10	1.55
15	1.79
30	1.93

(U) One sees that α increases monotonically with frequency. This means that transmission loss increases with frequency. At these frequencies, the attenuation loss in water is so small that it would not account for this change with frequency. Table 4 below gives transmission loss values at ranges of 10, 50, 100, 400 and 1000 n.mi.

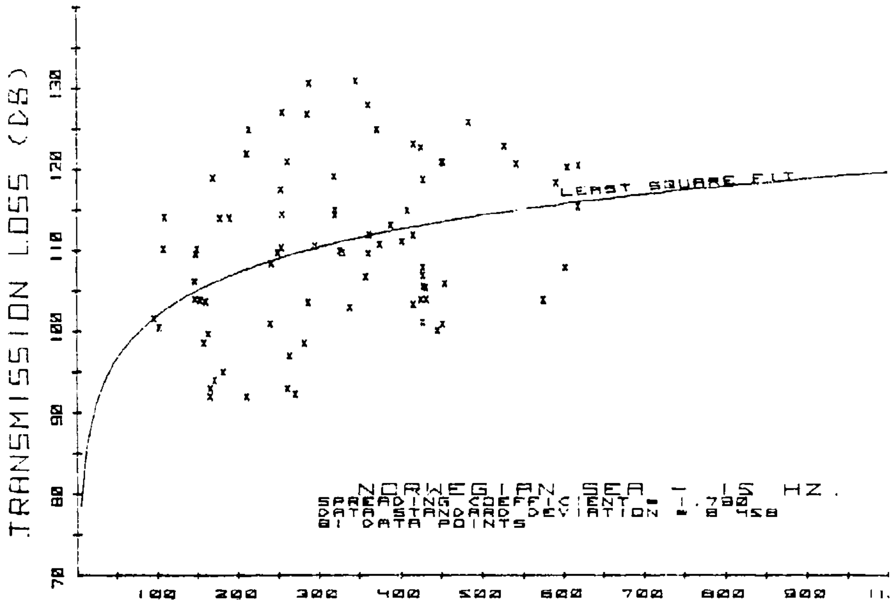


(a)

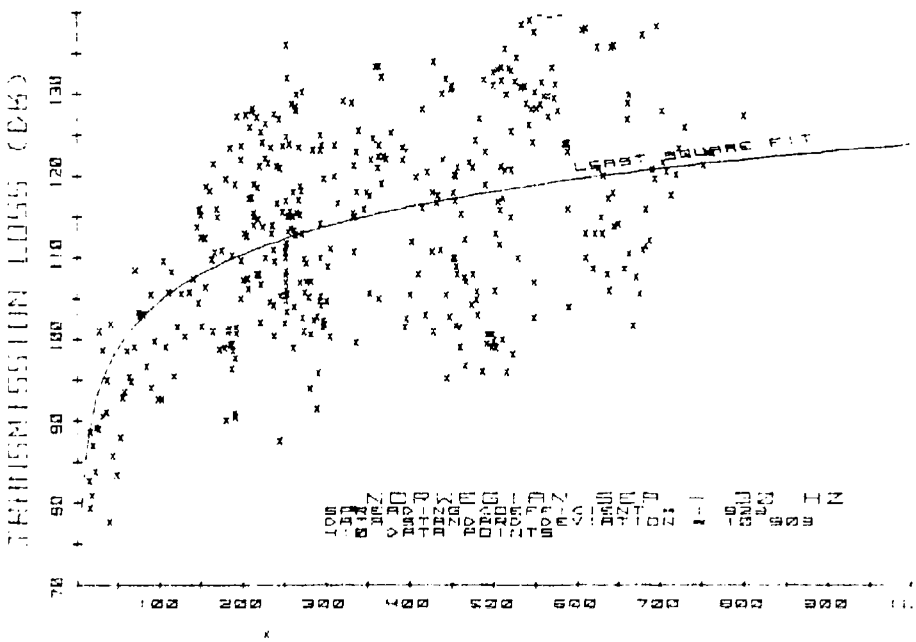


(b)

(S) Fig. 4 — Measured transmission loss at 5, 10, 15 and 30 Hz in the Norwegian Sea (S) (Continues)



(c)



(d)

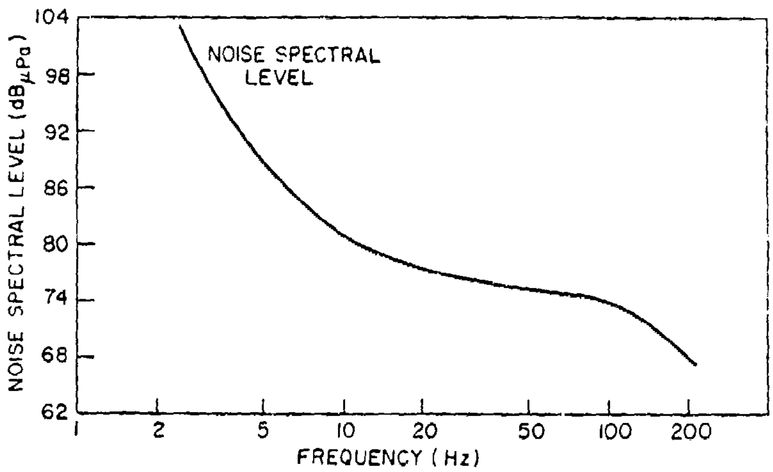
(S) Fig. 4 (Continued) — Measured transmission loss at 5, 10, 15 and 30 Hz in the Norwegian Sea (S) for all the frequencies considered. The transmission losses at 5, 10, 15 and 30 Hz were computed using equation 2 with the appropriate value of α. At other frequencies, transmission loss was computed by interpolating linearly between frequencies.

TABLE 4 (S)

Table of Transmission Loss for Norwegian Sea for Several Frequencies and Ranges

Frequency (Hz)	Range (nm)				
	10	50	100	400	1000
5	78.5	87.2	90.9	98.3	103.3
6	79.1	88.2	92.2	100.0	105.1
7	79.8	89.3	93.4	101.6	107.0
8	80.4	90.3	94.6	103.2	108.9
9	81.0	91.4	95.9	104.8	110.7
10	81.6	92.4	97.1	106.4	112.6
11	82.1	93.3	98.1	107.7	114.0
12	82.6	94.1	99.0	108.9	115.5
13	83.1	94.9	100.0	110.2	116.9
14	83.5	95.7	101.0	111.5	118.4
15	84.0	96.5	101.9	112.7	119.8
16	84.1	96.7	102.1	112.9	120.1
17	84.2	96.9	102.3	113.2	120.4
18	84.3	97.0	102.5	113.4	120.7
19	84.4	97.2	102.7	113.7	120.9
20	84.5	97.3	102.9	113.9	121.2
25	85.0	98.1	103.8	115.1	122.6

(U) Ambient noise was simultaneously measured at 5, 10, 15, and 30 Hz (see Figure 5). Table 5 gives the mean ambient noise as a function of frequency. Ambient noise for frequencies other than 5, 10, 15, and 30 Hz is obtained by linear interpolation in frequency between the measured values.



(S) Fig. 5 — Measured ambient noise levels vs. frequency in the Norwegian Sea

TABLE 5 (S)

Ambient Noise in the Norwegian Sea

Frequency (Hz)	Ambient Noise (dB//1µPa)
5	88.2
6	86.7
7	85.2
8	83.7
9	82.2
10	80.7
11	80.3
12	79.8
13	79.4
14	78.9
15	78.5
16	78.4
17	78.2
18	78.1
19	77.9
20	77.8
25	77.1

Environmental Data - Atlantic Ocean

(U) In May 1969, NRL conducted a long range acoustic experiment in the Atlantic Ocean. The experiment measured transmission loss at 13.9 Hz from Antigua, West Indies to the Grand Banks (reference 2). The result is shown in Figure 6. The mean transmission loss data fits the function

$$TL(R) = \begin{cases} 66.13 + 16.11 \log_{10}(R) & R < 400 \text{ nm} \\ 108 & R \geq 400 \text{ nm} \end{cases} \quad (3)$$

where R is in nautical miles.

(U) Beyond 400 nautical miles, the transmission loss changes very little. This is due to a change in the sound velocity profile which increases the coupling of the source to the deep sound channel.

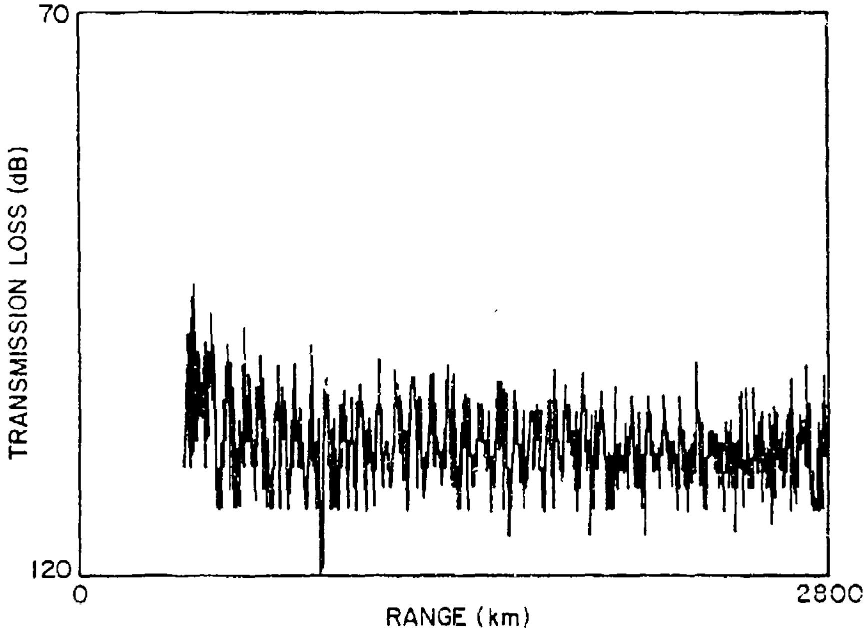


Fig. 6 — Measured transmission loss at 13.9 Hz
in the Atlantic Ocean

(U) Transmission loss was not measured at any other frequency than 13.9 Hz. Therefore, one cannot accurately predict how transmission loss in the Atlantic Ocean will change with frequency. But, one can hypothesize that frequency dependence in the Atlantic Ocean is approximately the same as in the Norwegian Sea. If one assumes: (1) that the spreading coefficient increases by the same amount in both areas as frequency increases from 5 to 10 to 15 to 30 Hz, and (2) α equals 1.611 at 13.9 Hz, then Table 6 below gives α for different frequencies.

TABLE 6 (U)

Values of Spreading Coefficient, α, in Atlantic Ocean for Different Frequencies

Frequency (Hz)	α
5.	1.114
10.	1.424
13.9	1.611
15.	1.664
30.	1.794

The transmission loss at 5, 10, 13.9, 15, and 30 Hz then has the form

$$\begin{aligned} TL(R) &= 66.13 + 10\,\alpha \log_{10}(R) & R < 400 \\ &\ 66.13 + 10\,\alpha \log_{10}(400) & R \geq 400 \end{aligned} \qquad (4)$$

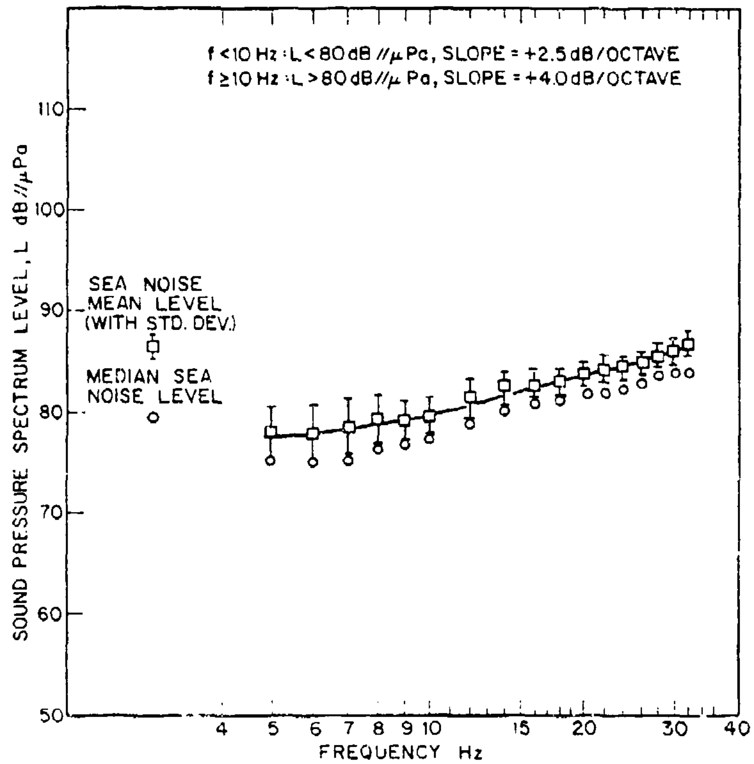
where α corresponds to the appropriate frequency in Table 6. Table 7 gives transmission losses for several frequencies. The losses at frequencies other than 5, 10, 13.9, 15, and 30 Hz are obtained by linear interpolation in frequency.

(U) The ambient noise measurements for the Atlantic Ocean were made near the Azores Islands in October 1973 (reference 6). See Figure 7 for the noise levels vs frequency. Table 8 gives mean values of ambient noise.

TABLE 7 (U)

Table of Transmission Loss for Atlantic Ocean

Frequency	Range (n.mi.)				
	10	50	100	400	1000
5	77.3	85.1	88.4	95.1	95.1
6	77.9	86.1	89.7	96.7	96.7
7	78.5	87.2	90.0	98.3	98.3
8	79.1	88.2	92.1	100.0	100.0
9	79.8	89.3	93.4	101.6	101.6
10	80.4	90.3	94.6	103.2	103.2
11	80.9	91.1	95.6	104.4	104.4
12	81.3	92.0	96.5	105.7	105.7
13	81.8	92.8	97.5	106.9	106.9
13.9	82.2	93.5	98.4	108.0	108.0
14	82.3	93.6	98.5	108.2	108.2
15	82.8	94.4	99.4	109.4	109.4
16	82.9	94.5	99.6	109.7	109.7
17	82.9	94.7	99.8	109.9	109.9
18	83.0	94.8	99.9	110.1	110.1
19	83.1	95.0	100.1	110.3	110.3
20	83.2	95.1	100.3	110.6	110.6
25	83.6	95.9	101.1	111.7	111.7



(S) Fig. 7 — Measured ambient noise levels vs. frequency in the Atlantic Ocean

TABLE 8 (U)

Ambient Noise in Atlantic Ocean

Frequency (Hz)	N (dB//1μPa)
5	78.5
6	79.2
7	79.7
8	80.2
9	80.6
10	81.0
11	81.5
12	82.1
13	82.5
14	82.9
15	83.3
16	83.7
17	84.1
18	84.4
19	84.7
20	85.0
25	86.3

Blade Rate Recognition Differential

(S) With the assumption of a 0.1 hz. analyzer and a 10 minute integration time, one can compute a signal recognition differential for blade rate lines. DiFranco and Rubin, reference 8, give 11.2 dB as the average output signal to noise ratio needed for a 50% probability of detection with 10^{-6} probability of false alarm. The processing gain for narrowband filtering and time integration is

$$PG = 5 \log_{10} \frac{T_{int}}{W_a} \qquad (4)$$

where T_{int} is the processor integration time in seconds and W_a is the signal bandwidth in Hz. For T_{int} = 10 minutes = 600 seconds and W_a = .1 Hz, the processing gain becomes

$$PG = 5 \log_{10} \frac{600}{.1} = 5 \log_{10} 6000 = 18.9 \text{ dB} \qquad (5)$$

This gives a recognition differential of

$$RD = 11.2 - 18.9 = -7.7 \text{ dB} \qquad (6)$$

Therefore, an average signal to noise ratio of -7.7 dB is needed at the array output to achieve a 50% probability of detection with a 10 minute integration period and with W_a = .1 Hz.

(S) For undersea surveillance purposes it is often assumed that one contact (detection/localization) per day is adequate. To meet a requirement for a 0.95 probability of at least one detection in 24 hours a reduced RD is found as follows. One can assume that there are at least 24 independent samples of signal to noise ratio in a day. The probability that one or more of these samples exceeds the detection threshold is

$$1 - (1 - x)^{24} \qquad (7)$$

where x is the probability that each individual sample exceeds the detection threshold. To achieve a 0.95 probability that one or more detections occurs in a 24 hour period, x must exceed only 0.117. So the recognition differential can be reduced to reflect a change from 0.50 to 0.117 probability of detection in a 10 minute integration period.

(U) To make this change in recognition differential, one must know the distribution of the signal to noise ratio due to fluctuation effects. Here, the signal to noise ratio is assumed normally distributed.

(C) To find the standard deviation of the signal to noise fluctuations, one must first assign standard deviations to the components of the signal to noise ratio. The components of interest are transmission loss, source level, and ambient noise. The assumed standard deviations are:

TABLE 9 (C)

Standard Deviations of Components of Signal to Noise

Fluctuation Source	Symbol	Standard Deviation
Transmission Loss	σ_{TL}	8
Source Level	σ_{SL}	7
Ambient Noise	σ_N	7

(S) The standard deviation for the Norwegian Sea transmission loss data is given in Figures 4; the standard deviation of the Atlantic Ocean transmission loss data can be estimated from Figure 6. A standard deviation of 8 dB was chosen as representative of both locations at all frequencies. The blade rate source level will vary with target aspect and from submarine to submarine within the same class. In figure 1, the aspect variation has a standard deviation of 5 dB. If one independently adds about 5 dB variation for submarine to submarine differences, σ_{SL} becomes 7 dB. The ambient noise standard deviation, σ_N, of 7 dB was chosen slightly larger than the values shown in Figure 7.

(C) The signal to noise fluctuation is the sum of fluctuations in transmission loss, source level, and ambient noise. If independence assumptions are made, the standard deviation of the signal to noise fluctuation, $\sigma_{S/N}$, is

$$\sigma_{S/N} \cong \sqrt{\sigma^2_{TL} + \sigma^2_{SL} + \sigma^2_{N}} = \sqrt{162} \cong 13 \text{ dB} \qquad (8)$$

(C) On the cumulative normal distribution, the .117 point is 1.19 σ below the distribution mean where is the standard deviation of the distribution. This means that the recognition differential for .117 probability of detection is 1.19 $\sigma_{S/N}$ ($\cong$ 15.5 dB) below the recognition differential for 50% probability of detection. This gives a recognition differential of

$$-7.7 \text{ dB} - 15.5 \text{ dB} = -23.2 \text{ dB} \qquad (9)$$

If one assumes a 3 dB degradation of signal to noise ratio in operational situations, one gets a recognition differential of approximately -20dB.

Detection Performance

(U) The array gain necessary to meet the previously discussed detection requirement is an inverse measure of the feasibility of VLF blade rate detection. The less array gain needed, the more likely such an array can be constructed and the more feasible the system. The needed array gain, AG, is found by setting signal excess to zero and solving the usual sonar equation for AG

$$AG = N + RD - SL + TL \qquad (10)$$

where SL is source level, RD is recognition differential, N is ambient noise and TL is transmission loss. Tables 10A to 10E give the needed array gain in the Norwegian Sea for the five classes of submarines considered. Tables 11A to 11E give the needed array gain in the Atlantic Ocean. The source levels used in Tables 10 and 11 come from Table 1. The transmission loss values used in Tables 10 and 11 come from Tables 4 and 7 respectively. A line is drawn through the tables separating those array gains over +20 dB from the array gains less than +20 dB. Transmission loss as a function of frequency was not measured in the Atlantic Ocean. Tables 6 and 7 are based on the assumption that the transmission loss trends with frequency would also occur in the Atlantic. The calculations of required array gain for the Atlantic Ocean have been repeated in Table 12 using the same TL for all frequencies. (13.9 Hz values from Table 7).

Array Gain Considerations

(U) Tables 10, 11, and 12 show the minimum array gain needed for detection in each case. One must now consider to what extent these array gains can be achieved.

(U) It is assumed that beamforming is done by linearly summing the outputs of the individual hydrophones of the array. If the outputs of N hydrophones are summed, the theoretical array gain is $10 \log_{10} (N)$ in an isotropic noise field. However, this theoretical gain is not usually realizable, due to anisotropy of the noise field, lack of spatial coherence of the signal field, and spatial distortion of the array itself.

(C) Experiments have been done to measure the array gain of low-frequency towed arrays (reference 10). With a 2438m (8000 ft) towed array operating at 20 Hz, array gains of 12 to 13 dB were obtained. The theoretical array gain for the 32λ aperture is 18 dB. In this case, 16, 32, and 62 phone arrays performed at nearly the same array gain. A significant cause of system degradation appears to be spatial distortion in the towed array. One can assume that a straight horizontal array could achieve higher array gains.

(C) It seems reasonable to assume that array gains up to 20 dB can be obtained with linear arrays. Higher array gains may be possible using sophisticated beamforming and towing techniques and with other array configurations.

Conclusions and Recommendations

(C) The results tabulated in Tables 10-12 can be examined by several different methods. However, it is clear that, at transit speeds or greater, submarine blade rates provide detectable signal energy at achievable array gain values. An important issue is to determine the detection/speed characteristics for a given submarine in a given ocean area.

Table 10A: Table of Array Gain Needed for Detection in Norwegian Sea

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (NORWEGIAN)	88.2	86.7	85.2	83.7	82.2	80.7	80.3	79.8	79.4	78.9	78.5	78.4	78.2	78.1	77.9	77.8	77.1
RD	-20.0																
C-V CLASS SL	133.5	138.1	142.0	145.4	148.3	151.0	153.4	155.6	157.6	159.5	161.2	162.8	164.4	165.8	167.2	168.5	174.1
(N+RD-SL)	-65.3	-71.4	-76.8	-81.7	-86.1	-90.3	-93.1	-95.8	-98.2	100.6	102.7	104.4	106.2	107.7	109.3	110.7	117.0

Array Gain Needed (dB.)

AG + TL + (N+RD-SL)																	
SPEED (KTS.) C	5.1	6.2	7.4	8.5	9.7	10.9	12.1	13.3	14.5	15.7	17.0	18.2	19.5	20.7	22.0	23.3	
SPEED (KTS.) V	6.1	7.4	8.7	10.0	11.3	12.6	13.9	15.3	16.6	17.9	19.3	20.6	21.9	23.3	24.6	26.0	
RANGE (NM.)																	
10	13.2	7.7	3.0	-1.3	-5.1	-8.7	-11.0	-13.2	-15.1	-17.1	-18.7	-20.3	-22.0	-23.4	-24.9	-26.2	-32.0
50	21.9	16.8	12.5	8.6	5.3	2.1	.2	-1.7	-3.3	-4.9	-6.2	-7.7	-9.3	-10.7	-12.1	-13.4	-18.9
100	25.6	20.7	16.6	12.9	9.8	6.8	5.0	3.2	1.8	.4	-.8	-2.3	-3.9	-5.2	-6.6	-7.8	-13.2
400	33.0	28.6	24.8	21.5	18.7	16.1	14.6	13.1	12.0	10.9	10.0	8.5	7.0	5.7	4.4	3.2	-1.9
1000	38.0	33.7	30.2	27.2	24.6	22.3	20.9	19.7	18.7	17.8	17.1	15.7	14.2	13.0	11.6	10.3	5.6

Table 10B: Table of Array Gain Needed for Detection in Norwegian Sea

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (NORWEGIAN)	88.2	86.7	85.2	83.7	82.2	80.7	80.3	79.8	79.4	78.9	78.5	78.4	78.2	78.1	77.9	77.8	77.1
RD	-20.0																
Y CLASS SL	125.0	129.0	133.0	149.5	150.5	158.0	158.0	152.0	156.5	163.0	167.0	173.0	175.0	176.5	178.0	180.0	185.0
(N+RD-SL)	-56.8	-62.3	-67.8	-85.8	-88.3	-97.3	-97.7	-92.2	-97.1	104.1	108.5	114.6	116.8	118.4	120.1	122.2	127.9

Array Gain Needed (dB.)

AG = TL + (N+RD-SL)

SPEED (KTS.)	5.6	6.8	8.1	9.3	10.6	11.8	13.1	14.4	15.7	17.0	18.3	19.6	20.9	22.2	23.6	24.9	
RANGE (NM.)																	
10	21.7	16.8	12.0	-5.4	-7.3	-15.7	-15.6	-9.6	-14.0	-20.6	-24.5	-30.5	-32.6	-34.1	-35.7	-37.7	-42.9
50	30.4	25.9	21.5	4.5	3.1	-4.9	-4.4	1.9	-2.2	-8.4	-12.0	-17.9	-19.9	-21.4	-22.9	-24.9	-29.8
100	34.1	29.8	25.6	8.8	7.6	-.2	.4	6.8	2.9	-3.1	-6.6	-12.5	-14.5	-15.9	-17.4	-19.3	-24.1
400	41.5	37.7	33.8	17.4	16.5	9.1	10.0	16.7	13.1	7.4	4.2	-1.7	-3.6	-5.0	-6.4	-8.3	-12.8
1000	46.5	42.8	39.2	23.1	22.4	15.3	16.3	23.3	19.8	14.3	11.3	5.5	3.6	2.3	.8	-1.0	-5.3

Table 10C: Table of Array Gain Needed for Detection in Norwegian Sea

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (NORWEGIAN)	88.2	86.7	85.2	83.7	82.2	80.7	80.3	79.8	79.4	78.9	78.5	78.4	78.2	78.1	77.9	77.8	77.1
RD	-20.0																
D-II CLASS SL	131.0	143.0	148.5	145.7	147.7	152.0	161.0	167.0	167.0	166.5	166.0	166.0	166.5	167.0	168.0	169.0	177.0
(N+RD-SL)	-62.8	-76.3	-83.3	-82.0	-85.5	-91.3	100.7	107.2	107.6	107.6	107.5	107.6	108.3	108.9	110.1	111.2	119.9

Array Gain Needed (dB.)

AG = TL + (N+RD-SL)

SPEED (KTS.)	6.0	7.2	8.4	9.6	10.8	12.0	13.2	14.4	15.6	16.8	18.0	19.2	20.4	21.6	22.8	24.0	30.0
RANGE (NM.)																	
10	15.7	2.8	-3.5	-1.6	-4.5	-9.7	-18.6	-24.6	-24.5	-24.1	-23.5	-23.5	-24.1	-24.6	-25.7	-26.7	-34.9
50	24.4	11.9	6.0	8.3	5.9	1.1	-7.4	-13.1	-12.7	-11.9	-11.0	-10.9	-11.4	-11.9	-12.9	-13.9	-21.8
100	28.1	15.8	10.1	12.6	10.4	5.8	-2.6	-8.2	-7.6	-6.6	-5.6	-5.5	-6.0	-6.4	-7.4	-8.3	-16.1
400	35.5	23.7	18.3	21.2	19.3	15.1	7.0	1.7	2.6	3.9	5.2	5.3	4.9	4.5	3.6	2.7	-4.8
1000	40.5	28.8	23.7	26.9	25.2	21.3	13.3	8.3	9.3	10.8	12.3	12.5	12.1	11.8	10.8	10.0	2.7

Table 10D: Table of Array Gain Needed for Detection in Norwegian Sea

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (NORWEGIAN)	[illegible]8.2	86.7	85.2	83.7	82.2	80.7	80.3	79.8	79.4	78.9	78.5	78.4	78.2	78.1	77.9	77.8	77.1
RD	-20.0																
FUT SSGN CLASS SL	131.5	134.0	139.5	149.5	158.0	158.0	157.5	158.0	159.5	164.0	172.5	176.5	177.0	177.0	176.5	176.0	
(N+RD-SL)	-63.3	-67.3	-74.3	-85.8	-95.8	-97.3	-97.2	-98.2	100.1	105.1	114.0	118.1	118.8	118.9	118.6	118.2	

Array Gain Needed (dB.)

AG = TL + (N+RD-SL)

SPEED (KTS.)	8.0	9.6	11.2	12.8	14.4	16.0	17.6	19.2	20.8	22.4	24.0	25.6	27.2	28.8	30.4	32.0	40.
RANGE (NM.)																	
10	15.2	11.8	5.5	-5.4	-14.8	-15.7	-15.1	-15.6	-17.0	-21.6	-30.0	-34.0	-34.6	-34.6	-34.2	-33.7	
50	23.9	20.9	15.0	4.5	-4.4	-4.9	-3.9	-4.1	-5.2	-9.4	-17.5	-21.4	-21.9	-21.9	-21.4	-20.9	
100	27.6	24.8	19.1	8.8	.1	-.2	.9	.8	-.1	-4.1	-12.1	-16.0	-16.5	-16.4	-15.9	-15.3	
400	35.0	32.7	27.3	17.4	9.0	9.1	10.5	10.7	10.1	6.4	-1.3	-5.2	-5.6	-5.5	-4.9	-4.3	
1000	40.0	37.8	32.7	23.1	14.9	15.3	16.8	17.3	16.8	13.3	5.8	2.0	1.6	1.8	2.3	3.0	

Table 10E: Table of Array Gain Needed for Detection in Norwegian Sea

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (NORWEGIAN)	88.2	86.7	85.2	83.7	82.2	80.7	80.3	79.8	79.4	78.9	78.5	78.4	78.2	78.1	77.9	77.8	77.1
RD	-20.0																
FUR SSN CLASS SL	128.0	130.0	132.5	135.5	139.5	144.5	150.5	158.5	163.0	165.0	164.0	163.5	164.0	164.5	165.8	168.0	
(N+RD-SL)	-59.8	-63.3	-67.3	-71.8	-77.3	-83.8	-90.2	-98.7	103.6	106.1	105.5	105.1	105.8	106.4	107.9	110.2	

Array Gain Needed (dB.)

AG = TL + (N+RD-SL)

SPEED (KTS)	8.0	9.6	11.2	12.8	14.4	16.0	17.6	19.2	20.8	22.4	24.0	25.6	27.2	28.8	30.4	32.0	40.
RANGE (NM.)																	
10	18.7	15.8	12.5	8.6	3.7	-2.2	-8.1	-16.1	-20.5	-22.6	-21.5	-21.0	-21.6	-22.1	-23.5	-25.7	
50	27.4	24.9	22.0	18.5	14.1	8.6	3.1	-4.6	-8.7	-10.4	-9.0	-8.4	-8.9	-9.4	-10.7	-12.9	
100	31.1	28.8	26.1	22.8	18.6	13.3	7.9	.3	-3.6	-5.1	-3.6	-3.0	-3.5	-3.9	[illegible]	-7.3	
400	38.5	36.7	34.3	31.4	27.5	22.6	17.5	10.2	6.6	5.4	7.2	7.8	7.4	7.0	5.8	3.7	
1000	43.5	41.8	39.7	37.1	33.4	28.8	23.8	16.8	13.3	12.3	14.3	15.0	14.6	14.3	13.0	11.0	

Table 11A: Table of Array Gain Needed for Detection in Atlantic Ocean

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (ATLANTIC)	78.5	79.2	79.7	80.2	80.6	81.0	81.5	82.1	82.5	82.9	83.3	83.7	84.1	84.4	84.7	85.0	86.3
RD	-20.0																
C-V CLASS SL	133.5	138.1	142.0	145.4	148.3	151.0	153.4	155.0	157.6	159.5	161.2	162.8	164.4	165.8	167.2	168.5	174.1
(N+RD-SL)	-75.0	-78.9	-82.3	-85.2	-87.7	-90.0	-91.9	-93.5	-95.1	-96.6	-97.9	-99.1	100.3	101.4	102.5	103.5	107.8

Array Gain Needed (dB.)

AG = TL + (N+RD-SL)																		
SPEED (KTS.)	C	5.1	6.2	7.4	8.5	9.7	10.9	12.1	13.3	14.5	15.7	17.0	18.2	19.5	20.7	22.0	23.3	
	V	6.1	7.4	8.7	10.0	11.3	12.6	13.9	15.3	16.6	17.9	19.3	20.6	21.9	23.3	24.6	26.0	
RANGE (NM.)																		
10		2.3	-1.0	-3.8	-6.1	-7.9	-9.6	-11.0	-12.2	-13.3	-14.3	-15.1	-16.2	-17.4	-18.4	-19.4	-20.3	-24.2
50		10.1	7.2	4.9	3.0	1.6	.3	-.8	-1.5	-2.3	-3.0	-3.5	-4.6	-5.6	-6.6	-7.5	-8.4	-11.9
100		13.4	10.8	8.6	6.9	5.7	4.6	3.7	3.0	2.4	1.9	1.5	.5	-.5	-1.5	-2.4	-3.2	-6.7
400		20.1	17.8	16.0	14.8	13.9	13.2	12.5	12.2	11.8	11.6	11.5	10.6	9.6	8.7	7.8	7.1	3.9
1000		20.1	17.8	16.0	14.8	13.9	13.2	12.5	12.2	11.8	11.6	11.5	10.6	9.6	8.7	7.8	7.1	3.9

Table 11B: Table of Array Gain Needed for Detection in Atlantic Ocean

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (ATLANTIC)	78.5	79.2	79.7	80.2	80.6	81.0	81.5	82.1	82.5	82.9	83.3	83.7	84.1	84.4	84.7	85.0	86.3
RD	-20.0																
Y CLASS SL	125.0	129.0	133.0	149.5	150.5	158.0	158.0	152.0	156.5	163.0	167.0	173.0	175.0	176.5	178.0	180.0	185.0
(N+RD-SL)	-66.5	-69.8	-73.3	-89.3	-89.9	-97.0	-96.5	-89.9	-94.0	100.1	103.7	109.3	110.9	112.1	113.3	115.0	118.7

Array Gain Needed (dB.)

AC = TL +(N+RD-SL)																	
SPEED (KTS.)	5.6	6.8	8.1	9.3	10.6	11.8	13.1	14.4	15.7	17.0	18.3	19.6	20.9	22.2	23.6	24.9	
RANGE (NM.)																	
10	10.8	8.1	5.2	-10.2	-10.1	-16.6	-15.6	-8.6	-12.2	-17.8	-20.9	-26.4	-28.0	-29.1	-30.2	-31.8	-35.1
50	18.6	16.3	13.9	-1.1	-.6	-6.7	-5.4	2.1	-1.2	-6.5	-9.3	-14.8	-16.2	-17.3	-18.3	-19.9	-22.8
100	21.6	19.9	17.6	2.8	3.5	-2.4	-.9	6.6	3.5	-1.6	-4.3	-9.7	-11.1	-12.2	-13.2	-14.7	-17.6
400	28.6	26.9	25.0	10.7	11.7	6.2	7.9	15.8	12.9	8.1	5.7	.4	-1.0	-2.0	-3.0	-4.4	-7.0
1000	28.6	26.9	25.0	10.7	11.7	6.2	7.9	15.8	12.9	8.1	5.7	.4	-1.0	-2.0	-3.0	-4.4	-7.0

Table 11C: Table of Array Gain Needed for Detection in Atlantic Ocean

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (ATLANTIC)	78.5	79.2	79.7	80.2	80.6	81.0	81.5	82.1	82.5	82.9	83.3	83.7	84.1	84.4	84.7	85.0	86.3
RD	-20.0																
D-II CIASS SL	131.0	143.0	148.5	145.7	147.7	152.0	161.0	167.0	167.0	166.5	166.0	166.0	166 5	167.0	168.0	169.0	177.0
(N+RD-SL)	-72.5	-83.8	-88.8	-85.5	-87.1	-91.0	-99.5	104.9	104.5	103.6	102.7	102.3	102.4	102.6	103.3	104.0	110.7

Array Gain Needed (dB.)

AG = TL + (N+RD-SL)

SPEED (KTS.)	6.0	7.2	8.4	9.6	10.8	12.0	13.2	14.4	15.6	16.8	18.0	19.2	20.4	21.6	22.8	24.0	30.0
RANGE (NM.)																	
10	4.8	-5.9	-10.3	-6.4	-7.3	-10.6	-18.6	-23.6	-22 7	-21.3	-19.9	-19.4	-19.5	-19.6	-20.2	-20.8	-27.1
50	12.6	2.3	-1.6	2.7	2.2	-.7	-8.4	-12.9	-11.7	-10.0	-8.3	-7.8	-7.7	-7.8	-8.3	-8.9	-14.8
100	15.9	5.9	2.1	6.6	6.3	3.6	-3.9	-8.4	-7.0	-5.1	-3.3	-2.7	-2.6	-2.7	-3.2	-3.7	-9.6
400	22.6	12.9	9.5	14.5	14.5	12.2	4.9	.8	2.4	4.6	6.7	7.4	7.5	7.5	7.0	6.6	1.0
1000	22.6	12.9	9.5	14.5	14.5	12.2	4.9	.8	2.4	4.6	6.7	7.4	7.5	7.5	7.0	6.6	1.0

Table 11D: Table of Array Gain Needed for Detection in Atlantic Ocean

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
RD	-20.0																
FUT SSGN SL	131.5	134.0	139.5	149.5	158.0	158.0	157.5	158.0	159.5	164.0	172.5	176.5	177.0	177.0	176.5	176.0	
(N+RD-SL)	-73.0	-74.8	-79.8	-89.3	-97.4	-97.0	-96.0	-95.9	-97.0	101.1	109.2	112.6	112.9	112.6	111.8	111.0	
Array Gain Needed (dB.)																	
AG = TL + (N+RD-SL)																	
SPEED (KTS.)	8.0	9.6	11.2	12.8	14.4	16.0	17.6	19.2	20.8	22.4	24.0	25.6	27.2	28.8	30.4	32.0	40.0
RANGE (NM)																	
10	4.3	3.1	-1.3	-10.2	-17.6	-16.6	-15.1	-14.6	-15.2	-18.8	-26.4	-29.9	-30.0	-29.6	-28.7	-27.8	
50	12.1	11.3	7.4	-1.1	-8.1	-6.7	-4.9	-3.9	-4.2	-7.5	-14.8	-18.3	-18.2	-17.8	-16.8	-15.9	
100	15.4	14.9	11.1	2.8	-4.0	-2.4	-.4	.6	.5	-2.6	-9.8	-13.2	-13.1	-12.7	-11.7	-10.7	
400	22.1	21.9	18.5	10.7	4.2	6.2	8.4	9.8	9.9	7.1	.2	-3.1	-3.0	-2.5	-1.5	-.4	
1000	22.1	21.9	18.5	10.7	4.2	6.2	8.4	9.8	9.9	7.1	.2	-3.1	-3.0	-2.5	-1.5	-.4	

Table 11E: Table of Array Gain Needed for Detection in Atlantic Ocean

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (ATLANTIC)	78.5	79.2	79.7	80.2	80.6	81.0	81.5	82.1	82.5	82.9	83.3	83.7	84.1	84.4	84.7	85.0	86.3
RD	-20.0																
FUT SSN CLASS SL	128.0	130.0	132.5	135.5	139.5	144.5	150.5	158.5	163.0	165.0	164.0	163.5	164.0	164.5	165.8	168.0	
(N+RD-SL)	-69.5	-70.8	-72.8	-75.3	-78.9	-83.5	-89.0	-96.4	100.5	102.1	100.7	-99.8	-99.9	100.1	100.8	103.0	

Array Gain Needed (dB.)

AG = TL + (N+RD-SL)

SPEED (KTS.)	8.0	9.6	11.2	12.8	14.4	16.0	17.6	19.2	20.8	22.4	24.0	25.6	27.2	28.8	30.4	32.0	40.0
RANGE (NM.)																	
10	7.8	7.1	5.7	3.8	.9	-3.1	-8.1	-15.1	-18.7	-19.8	-17.9	-16.9	-17.0	-17.1	-18.0	-19.8	
50	15.6	15.3	14.4	12.9	10.4	6.8	2.1	-4.4	-7.7	-8.5	-6.3	-5.3	-5.2	-5.3	-6.1	-7.9	
100	18.9	18.9	18.1	16.8	14.5	11.1	6.6	.1	-3.0	-3.6	-1.3	-.2	-.1	-.2	-1.0	-2.7	
400	25.6	25.9	25.5	24.7	22.7	19.7	15.4	9.3	6.4	6.1	8.7	9.9	10.0	10.0	9.2	7.6	
1000	25.6	25.9	25.5	24.7	22.7	19.7	15.4	9.3	6.4	6.1	8.7	9.9	10.0	10.0	9.2	7.6	

Table 12A: Table of Array Gain Needed for Detection in Atlantic Ocean With Transmission Loss Independent of Frequency

FREQUENCY (HZ.)		5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (ATLANTIC)		78.5	79.2	79.7	80.2	80.6	81.0	81.5	82.1	82.5	82.9	83.3	83.7	84.1	84.4	84.7	85.0	86.3
RD		-20.0																
C-V CLASS SL		133.5	138.1	142.0	145.4	148.3	151.0	153.4	155.0	157.6	159.5	161.2	162.8	164.4	165.8	167.2	168.5	174.1
(N+RD-SL)		-75.0	-78.9	-82.3	-85.2	-87.7	-90.0	-91.9	-93.5	-95.1	-96.6	-97.9	-99.1	100.3	101.4	102.5	103.5	107.8

Array Gain Needed (dB.)

AG = TL + (N+RD-SL)

SPEED (KTS.)																		
	C	5.1	6.2	7.4	8.5	9.7	10.9	12.1	13.3	14.5	15.7	17.0	18.2	19.5	20.7	22.0	23.3	
	V	6.1	7.4	8.7	10.0	11.3	12.6	13.9	15.3	16.6	17.9	19.3	20.6	21.9	23.3	24.6	26.0	

RANGE (NM.)																	
10	7.2	3.3	-.1	-3.0	-5.5	-7.8	-9.7	-11.3	-12.9	-14.4	-15.7	-16.9	-18.1	-19.2	-20.3	-21.3	-25.6
50	18.5	14.6	11.2	8.3	5.8	3.5	1.6	0.0	-1.6	-3.1	-4.4	-5.6	-6.8	-7.9	-9.0	-10.0	-14.3
100	23.4	19.5	16.1	13.2	10.7	8.4	6.5	4.9	3.3	1.8	.5	-.7	-1.9	-3.0	-4.1	-5.1	-9.4
400	33.0	29.1	25.7	22.8	20.3	18.0	16.1	14.5	12.9	11.4	10.1	8.9	7.7	6.6	5.5	4.5	.2
1000	33.[illegible]	2[illegible]1	25.7	22.8	20.3	18.0	16.1	14.5	12.9	11.4	10.1	8.9	7.7	6.6	5.5	4.5	.2

Table 12B: Table of Array Gain Needed for Detection in Atlantic Ocean
With Transmission Loss Independent of Frequency

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (ATLANTIC)	78.5	79.2	79.7	80.2	80.6	81.0	81.5	82.1	82.5	82.9	83.3	83.7	84.1	84.4	84.7	85.0	86.3
RD	-20.0																
Y CLASS SL	125.0	129.0	133.0	149.5	150.5	158.0	158.0	152.0	156.5	163.0	167.0	173.0	175.0	176.5	178.0	180.0	185.0
(N+RD-SL)	-66.5	-69.8	-73.3	-89.3	-89.9	-97.0	-96.5	-89.9	-94.0	100.1	103.7	109.3	110.9	112.1	113.3	115.0	118.7

Array Gain Needed (dB.)

AC = TL + (N+RD-SL)																	
SPEED (KTS.)	5.6	6.8	8.1	9.3	10.6	11.8	13.1	14.4	15.7	17.0	18.3	19.6	20.9	22.2	23.6	24.9	
RANGE (NM.)																	
10	15.7	12.4	8.9	-7.1	-7.7	-14.8	-14.3	-7.7	-11.8	-17.9	-21.5	-27.1	-28.7	-29.9	-31.1	-32.8	-36.5
50	27.0	23.7	20.2	4.2	3.6	-3.5	-3.0	3.6	-.5	-6.6	-10.2	-15.8	-17.4	-18.6	-19.8	-21.5	-25.2
100	31.9	28.6	25.1	9.1	8.5	1.4	1.9	8.5	4.4	-1.7	-5.3	-10.9	-12.5	-13.7	-14.9	-16.6	-20.3
400	41.5	38.2	34.7	18.7	18.1	11.0	11.5	18.1	14.0	7.9	4.3	-1.3	-2.9	-4.1	-5.3	-7.0	-10.7
1000	41.5	38.2	34.7	18.7	18.1	11.0	11.5	18.1	14.0	7.9	4.3	-1.3	-2.9	-4.1	-5.3	-7.0	-10.7

Table 12C: Table of Array Gain Needed for Detection in Atlantic Ocean With Transmission Loss Independent of Frequency

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (ATLANTIC)	78.5	79.2	79.7	80.2	80.6	81.0	81.5	82.1	82.5	82.9	83.3	83.7	84.1	84.4	84.7	85.0	86.3
RD	-20.0																
D-II CLASS SL	131.0	143.0	148.5	145.7	147.7	152.0	161.0	167.0	167.0	166.5	166.0	166.0	166.5	167.0	168.0	169.0	177.0
(N+RD-SL)	-72.5	-83.8	-88.8	-85.5	-87.1	-91.0	-99.5	104.9	104.5	103.6	102.7	102.3	102.4	102.6	103.3	104.0	110.7

Array Gain Needed (dB.)

AC = TL + (N+RD-SL)																	
SPEED (KTS.)	6.0	7.2	8.4	9.6	10.8	12.0	13.2	14.4	15.6	16.8	18.0	19.2	20.4	21.6	22.8	24.0	
RANGE (NM.)																	
10	9.7	-1.6	-6.6	-3.5	-4.9	-8.8	-17.3	-22.7	-22.3	-21.4	-20.5	-20.1	-20.2	-20.4	-21.1	-21.8	-28.5
50	21.0	9.7	4.7	8.0	6.4	2.5	-6.0	-11.4	-11.0	-10.1	-9.2	-8.8	-8.9	-9.1	-9.8	-10.5	-17.2
100	25.9	14.6	9.6	12.9	11.3	7.4	-1.1	-6.5	-6.1	-5.2	-4.3	-3.9	-4.0	-4.2	-4.9	-5.6	-12.3
400	35.5	24.2	19.2	22.5	20.9	17.0	8.5	3.1	3.5	4.4	5.3	5.7	5.6	5.4	4.7	4.0	-2.7
1000	35.5	24.2	19.2	22.5	20.9	17.0	8.5	3.1	3.5	4.4	5.3	5.7	5.6	5.4	4.7	4.0	-2.7

Table 12D: Table of Array Gain Needed for Detection in Atlantic Ocean
With Transmission Loss Independent of Frequency

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (ATLANTIC)	78.5	79.2	79.7	80.2	80.6	81.0	81.5	82.1	82.5	82.9	83.3	83.7	84.1	84.4	84.7	85.0	86.3
RD	-20.0																
FUT SSGN CLASS SL	131.5	134.0	139.5	149.5	158.0	158.0	157.5	158.0	159.5	164.0	172.5	176.5	177.0	177.0	176.5	176.0	
(N+RD-SL)	-73.0	-74.8	-79.8	-89.3	-97.4	-97.0	-96.0	-95.9	-97.0	101.1	109.2	112.8	112.9	112.6	111.8	111.0	

Array Gain Needed (dB.)

AG = TL + (N+RD-SL)

SPEED (KTS.)	8.0	9.6	11.2	12.8	14.4	16.0	17.6	19.2	20.8	22.4	24.0	25.6	27.2	28.8	30.4	32.0	40.0
RANGE (NM.)																	
10	9.2	7.4	2.4	-7.1	-15.2	-14.8	-13.8	-13.7	-14.8	-18.9	-27.0	-30.6	-30.7	-30.4	-29.6	-28.8	
50	20.5	18.7	13.7	4.2	-3.9	-3.5	-2.5	-2.4	-3.5	-7.6	-15.7	-19.3	-19.4	-19.1	-18.3	-17.5	
100	25.4	23.6	18.6	9.1	1.0	1.4	2.4	2.5	1.4	-2.7	-10.8	-14.4	-14.5	-14.2	-13.4	-12.6	
400	35.0	33.2	28.2	18.7	10.6	11.0	12.0	12.1	11.0	6.9	-1.2	-4.8	-4.9	-4.6	-3.8	-3.0	
1000	35.0	33.2	28.2	18.7	10.6	11.0	12.0	12.1	11.0	6.9	-1.2	-4.8	-4.9	-4.6	-3.8	-3.0	

Table 12E: Table of Array Gain Needed for Detection in Atlantic Ocean
With Transmission Loss Independent of Frequency

FREQUENCY (HZ.)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	25
NOISE (ATLANTIC)	78.5	79.2	79.7	80.2	80.6	81.0	81.5	82.1	82.5	82.9	83.3	83.7	84.1	84.4	84.7	85.0	86.3
RD	-20.0																
FIT SSN CLASS SL	128.0	130.0	132.5	135.5	139.5	144.5	150.5	158.5	163.0	165.0	164.0	168.5	164.0	164.5	165.8	168.0	
(N+RD-SL)	-69.5	-70.8	-72.8	-75.3	-78.9	-83.5	-89.0	-96.4	100.5	102.1	100.7	-99.8	-99.9	100.1	101.1	103.0	

Array Gain Needed (dB.)

AG = TL + (N+RD-SL)																	
SPEED (KTS.)	8.0	9.6	11.2	12.8	14.4	16.0	17.6	19.2	20.8	22.4	24.0	25.6	27.2	28.8	30.4	32.0	40.0
RANGE (NM.)																	
10	12.7	11.4	9.4	6.9	3.3	-1.3	-6.8	-14.2	-18.3	-19.9	-18.5	-17.6	-17.7	-17.9	-18.8	-20.8	
50	24.0	22.7	20.7	18.2	14.6	10.0	4.5	-2.9	-7.0	-8.6	-7.2	-6.3	-6.4	-6.6	-7.6	-9.5	
100	28.9	27.6	25.6	23.1	19.5	14.9	9.4	2.0	-2.1	-3.7	-2.3	-1.4	-1.5	-1.7	-2.7	-4.6	
400	38.5	37.2	35.2	32.7	29.1	24.5	19.0	11.6	7.5	5.9	7.3	8.2	8.1	7.9	6.9	5.0	
1000	38.5	37.2	35.2	32.7	29.1	24.5	19.0	11.6	7.5	5.9	7.3	8.2	8.1	7.9	6.9	5.0	

(S) Since there are a large number of combinations of submarine class, speed, frequency, array gain and range, a few cases have been selected for representative comparison. The C, Y, and future SSN represent current and projected Soviet capabilities. Figures 8-10 show the required array gain vs. submarine speed, with range as a parameter, for these three submarine types in the Norwegian Sea. The differences in the shapes of the curves are due to the assumed source level vs. speed characteristic (see Figures 2 and 3). By selecting an array gain figure which is achievable, the submarine speed vs. detection range can be determined. Such a result, for an array gain of 15 dB, is given in Figure 11. The solid lines are for the Norwegian Sea environment and the broken lines for the Atlantic Ocean. It is clear that, at patrol speeds of less than 8 knots, detection will be unlikely under the assumptions of this study. However, at transit speeds of 10-15 knots, detection ranges of 250-1000 n.mi. are anticipated for current C and Y classes. If future SSN submarines built by hostile nations are as quiet as assumed here, they will not be detectable by blade rate energy beyond 50-100 n.mi.

(U) To further compare the differences between the Norwegian Sea and Atlantic Ocean environments, the C, Y and future SSN classes were compared in terms of required array gain vs. speed at a range of 100 n.mi. (Figure 12). It can be seen that the AG/speed characteristics are quite similar, even though the noise characteristics vary differently with frequency.

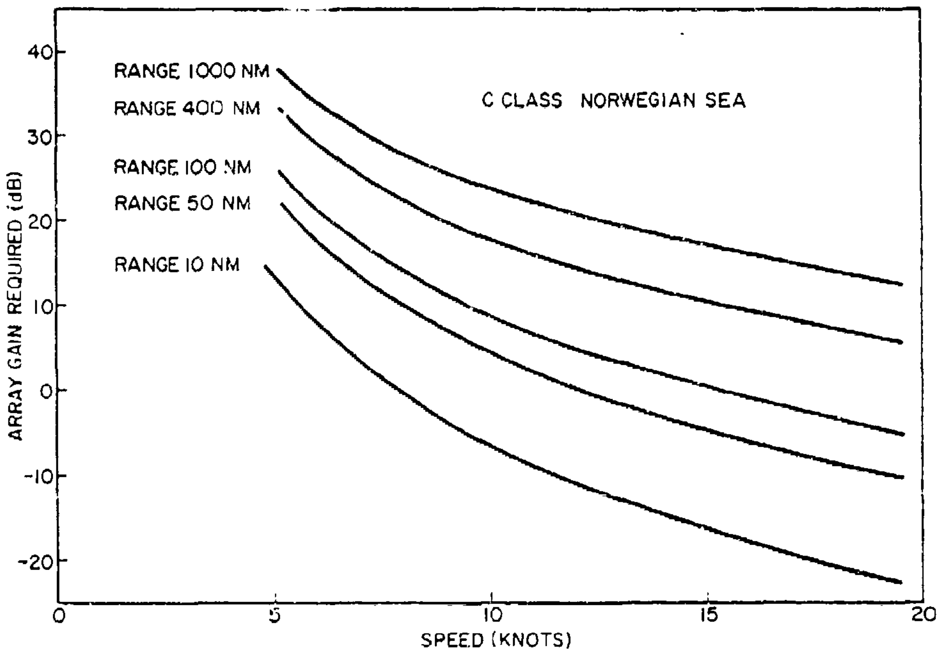
(C) Several factors employed in this analysis need further investigation. They are listed below:

(1) Does the transmission loss vary with frequency in the Atlantic Ocean as it does in the Norwegian Sea? What is the physical basis for the Norwegian Sea result?

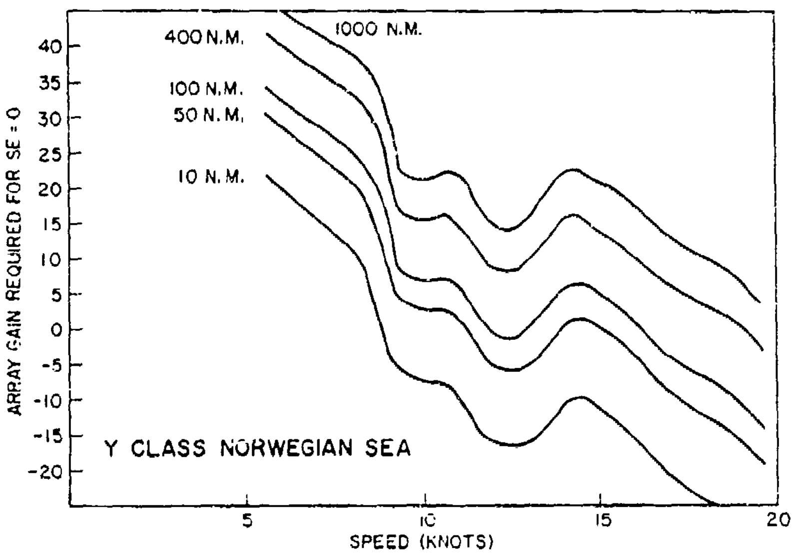
(2) The Atlantic Ocean noise results were obtained in the Mid-Atlantic Ridge area. The slope at low frequencies (< 10 Hz) is opposite to that of the Norwegian Sea data and needs further explanation.

(3) The radiated energy vs. speed characteristics for future hostile nation submarines is an area of uncertainty which requires continued attention and more refined intelligence measurement techniques to obtain low speed/low frequency data.

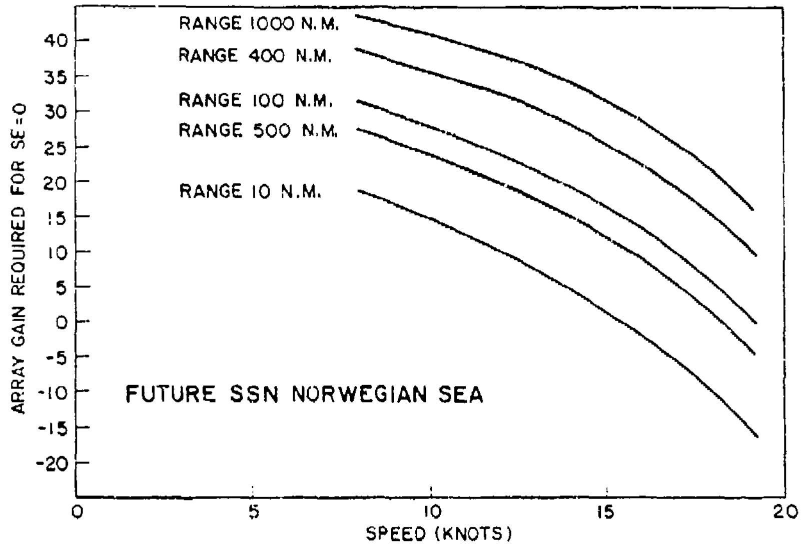
(4) In this report ambient noise is assumed to be isotropic. This is because the horizontal and vertical directionality of very low frequency noise is not well understood. If the directionality of very low frequency noise were well known, then detection ranges, computed in this report, could be increased significantly.



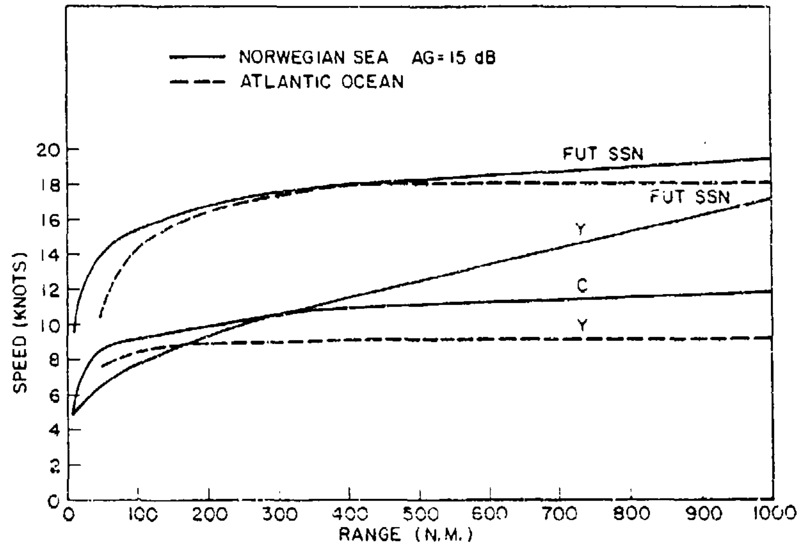
(C) Fig. 8 — Array gain vs submarine speed for C class submarines in the Norwegian Sea



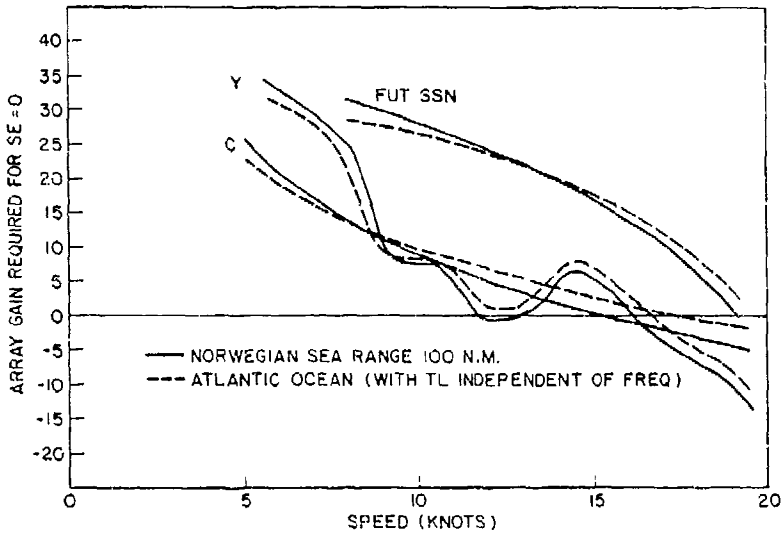
(S) Fig. 9 — Array gain vs. submarine speed for Y class submarines in the Norwegian Sea



(S) Fig. 10 — Array gain vs. submarine speed for future SSN in the Norwegian Sea



(S) Fig. 11 — Submarine speed vs. 0.5 probability of detection range for C, Y, and future SSN classes in the norwegian Sea



(S) Fig. 12 — Comparison of Norwegian Sea and Atlantic Ocean array gain requirement at a range of 100 n.mi.

(C) The possibility of improved passive detection under ice has not been addressed in this work. Very low frequencies are known to be best under ice due to the reduced scattering effects.

(S) The purpose of this report has been to examine the feasibility of VLF detection of submarines. The source levels of auxiliary lines of Russian submarines will probably decrease. Since blade lines are harder to quiet, we may be forced to use detection of blade lines. But as indicated above, there are substantial improvements in detection ranges which may be possible if the acoustic environment is properly exploited. It also appears that the frequency region of interest should be expanded to include the blade frequency region up to about 20 Hz rather than the conventional 1-10 Hz definitive initially assumed for this work.

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UNITED STATES GOVERNMENT

Memorandum

7100-038

DATE: 26 February 2004

REPLY TO ATTN OF: Burton G. Hurdle (Code 7103)

SUBJECT: REVIEW OF REF (A) FOR DECLASSIFICATION

TO: Code 1221.1

REF: (a) "Very Low Frequency Acoustic Detection" (U), William C. Dixon and C. Ray Rollins, Acoustics Division, NRL Memo Report 3467, March 1977 (C)

1. Reference (a) is a report on the detectability of blade rate frequency lines for several classes of Soviet submarines in the Norwegian Sea and North Atlantic. Transmission loss, ambient and array gain were considered.

2. The technology and equipment of reference (a) have long been superseded. The current value of these papers is historical

3. Based on the above, it is recommended that reference (a) be declassified and released with no restrictions

Burton G. Hurdle

BURTON G. HURDLE
NRL Code 7103

CONCUR:

Edward R. Franchi 03/01/2004

E.R. Franchi Date
Superintendent, Acoustics Division

CONCUR:

Tina Smallwood 3/3/04

Tina Smallwood Date
NRL Code 1221.1